

HELIOCENTRIC EVOLUTION OF KEY SPECIES IN COMET C/1995 O1 (HALE-BOPP). S.A. Stern (Southwest Research Institute, Boulder, CO 80302 USA, alan@everest.space.swri.edu), M. Womack (Pennsylvania State University at Erie, Erie, PA 16563 USA), M.C. Festou (Observatoire Midi Pyrénées, Toulouse, France).

Comet Hale-Bopp (C/1995 O1) presents the first opportunity to study physical and chemical changes in the coma of a bright, active comet at large heliocentric distances with modern millimeter-wavelength spectrometers. We have obtained mm-wave spectra of CH_3OH , CO, and H_2CO in Hale-Bopp when it was beyond 4 AU on 29 dates using the NRAO 12-m telescope on Kitt Peak, Arizona. The telescope receivers consist of dual-channel, cooled SIS mixers, which were tuned to reject the image sideband. The intermediate frequency (IF) in all cases was 1.5 GHz, and data were taken in the upper sideband. Temperature scales were established by the chopper-wheel method. The antenna temperatures, T_A , were determined from the corrected line radiation temperatures and the beam efficiency. The HPBW (θ) and beam efficiency (η) of the telescope was $\theta=27''$ and $\eta=0.51$ at ~ 230 GHz, $\theta=48''$ and $\eta=0.72$ at 145 GHz, and $\theta=54''$ and $\eta=0.84$ at 115 GHz.

The production rates for CO, CH_3OH , and H_2CO were derived using a standard isotropic nuclear outgassing model with photodissociative decay (Haser 1957). We assumed that each species is a parent with an expansion velocity of 0.3 km s^{-1} . If CH_3OH and H_2CO come from parent molecules, then vectorial model (Festou 1981) calculations reveal that the production rates would be less than 2 times higher for CH_3OH and ~ 1.5 times higher for H_2CO .

The production rate of CO, $Q(\text{CO})$, for Hale-Bopp is shown as a function of heliocentric distance in Figure 1. Filled circles are from our work; open triangles are from Jewitt et al. 1996; asterisks are from Biver et al. 1996. To minimize differences between the various datasets, measurements of the integrated line flux areas from each data source were used to calculate new column densities and production rates.

Notice that the CO production rate evolution displays three distinct regimes, with obvious breaks near 6.3 and 4.8 AU. CO was first detected in Hale-Bopp near 6.7 AU. Thereafter, $Q(\text{CO})$ increased at a rather steady rate from $r=6.7$ to 6.0 AU which we fit to a simple power law: $Q(\text{CO}) \sim r^{-11.9 \pm 4.3}$. However, at about 6 AU, the CO production then approximately leveled off, remaining about constant or perhaps very slightly increasing until the comet reached about 4.8 AU. In this regime, we find $Q(\text{CO}) \sim r^{-0.6 \pm 1.4}$. We suggest that the flattening of the CO production rate near 6 AU occurred owing to either surface quan-

tity or energy-rate limits. This renewed increase in $Q(\text{CO})$ near 4.8 AU produced a behavior characterized by $Q(\text{CO}) \sim r^{-3.8 \pm 0.6}$. To our knowledge, this fascinating, and clearly systematic change in CO production rate behavior across the 6 to 4 AU heliocentric distance range spanned has not been seen in any other comet. The fact that the power-law exponent of $Q(\text{CO})$ in regions A and C are so different is evidence that the mechanism generating the majority of the CO was different in each regime. The fact that CO production increased more steeply in region A than C is consistent with free CO release in region A and H_2O -controlled CO-release in region C (cf., Brown and Ziegler 1980). This is further supported by the fact that the sudden increase in CO production rate near 4.8 AU occurred near the point where the first detections of OH gas emission (and thus the initial, rapid increase in H_2O -ice sublimation, usually called "turn-on") occurred, near ~ 4.8 AU (Weaver et al. 1997; Crovisier et al. 1996). (A simple extrapolation of the OH detection backwards in heliocentric distance indicates that H_2O turned on quite close to 5 AU.)

Notice that the dramatic $Q(\text{CO})$ increase near 4.8 AU is also approximately coincident with both the first detection of methanol at ~ 5.0 AU (Womack et al. 1996), and the first detections of HCN at ~ 4.7 AU (Jewitt et al. 1996). The fact that constraining negative searches (by others) were made for CH_3OH and HCN before detections were achieved implies that these two were not present in significant quantities until about (or perhaps at) the time of the onset of vigorous H_2O -ice sublimation. Concerning H_2O -ice itself, we point out that because the Hubble Space Telescope observations which detected OH as a proxy for H_2O (Weaver et al. 1996) were much sparser in time than mm-wave CH_3OH searches, the actual onset of H_2O -ice sublimation is probably best identified with the onset of CH_3OH near 5 AU.

The detection of CH_3OH and HCN, near the time of the onset of water sublimation, like the additional CO (cf., Figure 1), argues that these species were released into Hale-Bopp's coma *as a result* of the H_2O -ice sublimation. This could occur if, for example, these molecules were more abundant in the water-ice zone than the (lower) CO-ice zone, or perhaps more probably if the water-ice sublimation (being more vigorous) was capable of entraining larger grains that

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were richer in these species, which in turn later disintegrated to release the minor species.

We will show that while the OH production rate follows the $Q(\text{OH}) \sim r^{-7.1 \pm 0.1}$, but $Q(\text{CO}) \sim r^{-3.8 \pm 0.6}$, and $Q(\text{CH}_3\text{OH}) \sim r^{-1.5 \pm 0.6}$. These different production rate slopes indicate that, while the production of CO, CH₃OH and OH may be causally related, they are not stoichiometrically coupled.

Additional facts are revealed by examining line shapes and velocity offsets in our data. The fact that the CO emission is consistently blueshifted by a few hundred meters per second is strong evidence that the bulk of the CO arose at these heliocentric distances from a jet-like source on the sunward side of the comet. (Atmospheric models in which the CO outflow is restricted to solid angles consistent with the data lead to production rates that do not differ by more than 30%). We see no evidence for a significant source of distributed CO-emission in the velocity spectra beyond 4 AU.

We will also show that the CH₃OH and H₂CO emissions are essentially at rest with respect to the comet's frame. The near-zero velocity relative to the comet and symmetric line profiles of formaldehyde and methanol are difficult to understand unless these species are being produced by the photodissociation of heavier molecules in the coma, such as CHON grains (e.g., Huebner et al. 1987) carried in the water-dominated outflow. The wide (1–2 km s⁻¹) line profiles of both formaldehyde and methanol are far wider than the linewidth of CO, further supporting this conclusion. In the same regard, we point out that in comets observed at heliocentric distances near 1 AU, thermal conditions create linewidths of CO, CH₃OH, and H₂CO that are all of order 1–2 km sec, masking the signatures observed at 4–6 AU that suggest that methanol and formaldehyde originate as disso-

ciation products of a heavier parent molecule.

Although H₂CO has long been thought to be a daughter species in cometary comae, that CH₃OH also seems to be a daughter product is unexpected, and should provide valuable new insights into the nature of cometary grains and the environment in which this and presumably other comets were formed.

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